

Study of CP violation in Λ_c^+ decay

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In this paper, we study CP violation in $\Lambda_c^+ \rightarrow BP$ and $\Lambda_c^+ \rightarrow BV$ decays, where B, P and V denote a light spin- $\frac{1}{2}$ baryon, pseudoscalar and a vector meson respectively. In these processes the T odd CP violating triple-product (TP) correlations are examined. The genuine CP violating observables which are composed of the helicity amplitudes occurring in the angular distribution are constructed. Experimentally, by performing a full angular analysis it is shown how one may extract the helicity amplitudes and then obtain the TP asymmetries. We estimate the TP asymmetries in Λ_c^+ decays to be negligible in the standard model making these processes an excellent place to look for new physics. Taking a two Higgs doublet model, as an example of new physics, we show that large TP asymmetries are possible in these decays. Finally, we discuss how BES-III and Super τ -Charm experiments will be sensitive to these CP violating signals in Λ_c^+ decays.

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Thanks to the effort that the B factories have made over the last decade, it has been confirmed that the Cabibbo-Kobayashi-Maskawa (CKM) mechanism embedded in the standard model (SM) is the leading source of CP violation in the quark sector [1, 2]. Especially for the s -quark and b -quark sectors, impressive agreement between theory and experiment has been achieved [3, 4]. However, due to the small contribution from the SM, CP violation in the c -quark sector is tiny making it an excellent place to look for new CP violating signals from new physics (NP). While CP violation has not been seen presently in the charm sector [5–8], more precise measurements will be necessary to test the SM predictions of CP violation in this sector. [9–11]. One can also search for new CP violating phases by looking at baryon decays containing a charm quark. Studying CP violation in Λ_c^+ baryon decays opens up another front in the search for NP signals in the charm sector. The CP violation parameter \mathcal{A} in Λ_c^+ decaying to $\Lambda\pi^+$ has been measured by the FOCUS Collaboration in 2005 with the result of $\mathcal{A} = -0.07 \pm 0.19 \pm 0.12$ [12], where the errors are statistical and systematic, respectively. The Particle Data Group (PDG) value is $\mathcal{A} = -0.07 \pm 0.31$ [13]. Hence this measurement does not show evidence of CP violation and is therefore consistent with the SM. However, the errors in the measurement are large and no definite conclusion about the absence or presence of new CP violating phases can be made at this time.

Note that the parameter \mathcal{A} is a CP violating asymmetry constructed out of the up-down asymmetry α , and is a direct CP violating asymmetry. Therefore, $\mathcal{A} \sim \sin \delta$, where δ is the strong phase difference between the two amplitudes in the decay. Thus, if δ is small then \mathcal{A} may be small even in the presence of new CP violating phases beyond the SM. There are theoretical estimates, based on baryon chiral perturbation theory, that indicate that the strong phases from $\Lambda - \pi$ rescattering are small at the Ξ

mass [14, 15]. It is not obvious that the results of baryon chiral perturbation theory can be applied to Λ_c^+ decays as the pion from the $\Lambda_c^+ \rightarrow \Lambda\pi$ transition has energy, $E_\pi = 875$ MeV, which is close to the cut-off $\sim GeV$ for chiral perturbation theory. It is interesting to note that if one applies the same equations in Ref. [14, 15] but evaluated at the Λ_c^+ mass then one gets small strong phases of a few degrees. We start with Ref. [14], where it was shown that the S -wave phase shift vanishes in the leading order in baryon chiral perturbation theory. The P -wave phase shift δ_1 can be expressed as,

$$\delta_1 = -\frac{(E_\pi^2 - m_\pi^2)^{3/2}}{12\pi f_\pi^2} \left[\frac{1}{4} \frac{g_{\Sigma\pi}^2}{E_\pi + m_\Sigma - m_\Lambda} + \frac{3}{4} \frac{g_{\Sigma\Lambda}^2}{E_\pi + m_\Lambda - m_\Sigma} - \frac{4}{3} \frac{g_{\Sigma^*\Lambda}^2}{E_\pi + m_{\Sigma^*} - m_\Lambda} \right] \quad (1)$$

where $f_\pi \sim 132$ MeV is the pion decay constant and $g_{\Sigma\Lambda}^2 \simeq 1.44$ is the strong Σ - $\Lambda\pi$ coupling. The strong coupling of the spin- $\frac{3}{2}$ isotriplet Σ^* to $\Lambda\pi$ is determined to be $g_{\Sigma^*\Lambda}^2 \simeq 1.49$ [14]. Evaluating the phase shift at $E_\pi = 875$ MeV we find $\delta_1 \simeq -0.05^\circ$. In Ref. [15], the S wave phase shift was generated in $\Lambda - \pi$ scattering, mainly through the exchange of $\frac{1}{2}^-\Sigma(1750)$ (denoted by Σ'). In this case the S -wave phase shift δ_0 is given by,

$$\delta_0 = -\frac{1}{2\pi} \frac{g_{\Sigma'\Lambda}^2}{f_\pi^2} \frac{E_\pi^2(m_{\Sigma'} - m_\Lambda) \sqrt{E_\pi^2 - m_\pi^2}}{E_\pi^2 - (m_{\Sigma'} - m_\Lambda)^2}, \quad (2)$$

In Eq. (2), the coupling parameter $g_{\Sigma'\Lambda}$ can be obtained from the branching ratio for $\Sigma(1750) \rightarrow \Lambda\pi$. One has,

$$\Gamma[\Sigma(1750) \rightarrow \Lambda\pi] = \frac{g_{\Sigma'\Lambda}^2}{4\pi f_\pi^2} (m_{\Sigma'} - m_\Lambda)^2 \frac{p_\Lambda}{m_{\Sigma'}} (E_\Lambda + m_\Lambda), \quad (3)$$

where E_Λ and p_Λ are the energy and momentum of the Λ . The decay $\Sigma(1750) \rightarrow \Lambda\pi$ is not the dominant decay mode for $\Sigma(1750)$ and the branching ratio for this decay has not been measured though the decay

has been seen [13]. For an estimate of $g_{\Sigma^* \Lambda}$ we will assume $BR[\Sigma(1750) \rightarrow \Lambda\pi] \simeq BR[\Sigma(1750) \rightarrow \Sigma\pi] \leq 8\%$ [13] and setting the width of $\Sigma(1750)$ at 90 MeV [13] one obtains $g_{\Sigma^* \Lambda} \simeq 0.0058$. Substituting $g_{\Sigma^* \Lambda} = 0.0058$ and $E_\pi = 875 \text{ MeV}$ into Eq. (2), yields $\delta_0 \leq -3.4^\circ$.

Hence, chiral perturbation theory if applicable for Λ_c^+ decays, predict small strong phases. The key point that we want to emphasize here, is that \mathcal{A} will not reveal new non-SM CP violating phases if the strong phases are small and hence other CP violating signals that do not vanish with vanishing strong phases should also be measured.

In this Letter, we shall exploit the idea of “triple-product (TP) correlation” to construct the CP violating observables. These CP violating quantities are proportional to $\cos\delta$ and so can be large even with small strong phases. Hence these measurements are complementary to the direct CP violation measurements mentioned above. This type of CP violation is not new and has been considered previously in hyperon decays [16, 17], in B decays [18, 19] and in other processes. In the B system, Babar and Belle Collaborations have measured TP asymmetries [20–22] and these measurements provide strong limits on the CP violation originating from new physics [23]. The idea of TP correlation was also considered in the D meson sector [10, 24, 25]. In Ref. [10] the authors proposed to measure TP asymmetries in the D meson decays at BES-III and they estimated the errors in the determination of these asymmetries at BES-III and in other upcoming experiments. At this point it is worth pointing out that TP asymmetries in $D \rightarrow VV$ decays and Λ_c decays could probe different new physics because of the spin of the Λ_c . As an example, consider NP of the type $L_{NP} \sim \bar{s}\gamma_{AC}\bar{d}\gamma_B u$, where $\gamma_{A,B} = 1, \gamma_5$. In the factorization approximation this NP will not contribute to $D(D_s) \rightarrow VV$ decays but will contribute to $\Lambda_c \rightarrow BP$ decays. This is because, $\langle V|\bar{d}\gamma_B u|0 \rangle = \langle V|\bar{s}c|D(D_s) \rangle = 0$ while $\langle B|\bar{s}\gamma_{AC}|\Lambda_c \rangle, \langle P|\bar{d}\gamma_5 u|0 \rangle \neq 0$. Of course such interactions can contribute to $D(D_s) \rightarrow VP$ or $D(D_s) \rightarrow PP$ decays but triple product asymmetries cannot be constructed in such decays. It should be mentioned that renormalization effects to the NP operator above can generate new operator structures that will contribute to $D(D_s) \rightarrow VV$ decays but these effects should be suppressed in general. In general, if NP is detected in D decays, T.P asymmetry measurement in Λ_c decays can provide additional information about this NP.

An observable involving $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where each v_i can be a spin or momentum, is called a TP correlation. These TP’s are odd under naive time reversal (T) and hence constitute a T -odd CP violating observable. One can define an asymmetry quantity

$$A_T = \frac{N(\vec{v}_1 \cdot \vec{v}_2 \times \vec{v}_3 > 0) - N(\vec{v}_1 \cdot \vec{v}_2 \times \vec{v}_3 < 0)}{N_{total}}, \quad (4)$$

where the subscript T implies TP and N denotes the number of events. Equivalently one can define,

$$A_T = \frac{\Gamma(\vec{v}_1 \cdot \vec{v}_2 \times \vec{v}_3 > 0) - \Gamma(\vec{v}_1 \cdot \vec{v}_2 \times \vec{v}_3 < 0)}{\Gamma(\vec{v}_1 \cdot \vec{v}_2 \times \vec{v}_3 > 0) + \Gamma(\vec{v}_1 \cdot \vec{v}_2 \times \vec{v}_3 < 0)}. \quad (5)$$

For its conjugate channel, the similar quantity \bar{A}_T can be defined in the same way. It should be noted that there is a well-known technical complication: a non-zero TP correlation does not necessarily imply CP violation, since final state interactions (FSI) can fake it, namely the strong phase can also produce non-zero A_T (or \bar{A}_T) even though the weak phases are zero [10, 18, 19]. Yet comparing a TP correlation with its measurement in a CP conjugate transition allows one to distinguish genuine CP violation from FSI effects. One can define a true CP violating asymmetry as,

$$\mathcal{A}_T = \frac{1}{2}(A_T + \bar{A}_T), \quad (6)$$

and hence a nonzero \mathcal{A}_T is a CP violating signal.

We begin the first part of our analysis with $\Lambda_c^+ \rightarrow BP$ decays, where B denotes a light spin- $\frac{1}{2}$ baryon, P denotes a pseudoscalar. The amplitude for the decay $\Lambda_c^+ \rightarrow BP$ can be written as [26, 27]

$$\mathcal{M}_P \equiv A(\Lambda_c^+ \rightarrow BP) = \bar{u}_B(a + b\gamma_5)u_{\Lambda_c}, \quad (7)$$

where a and b are the parity violating and parity conserving amplitudes for the decay. In the rest frame of the Λ_c^+ one can reduce the above as,

$$\mathcal{M}_P \equiv A(\Lambda_c^+ \rightarrow BP) = \chi_B^\dagger (S + P\vec{\sigma} \cdot \hat{q})\chi_{\Lambda_c}, \quad (8)$$

where \hat{q} is a unit vector in the direction of the daughter baryon, the χ ’s are the two component spinors and

$$\begin{aligned} S &= \sqrt{2m_{\Lambda_c}(E_B + m_B)}a \\ P &= -\sqrt{2m_{\Lambda_c}(E_B - m_B)}b. \end{aligned} \quad (9)$$

The absolute value squared of \mathcal{M}_P can be obtained as,

$$\begin{aligned} |\mathcal{M}_P|^2 &= (|a|^2 - |b|^2)(m_B m_{\Lambda_c} + p_B \cdot s_{\Lambda_c} p_{\Lambda_c} \cdot s_B \\ &\quad - p_B \cdot p_{\Lambda_c} s_B \cdot s_{\Lambda_c}) \\ &\quad + (|a|^2 + |b|^2)(p_B \cdot p_{\Lambda_c} - m_B m_{\Lambda_c} s_B \cdot s_{\Lambda_c}) \\ &\quad + 2\text{Re}(ab^*)(m_{\Lambda_c} p_B \cdot s_{\Lambda_c} - m_B p_{\Lambda_c} \cdot s_B) \\ &\quad + 2\text{Im}(ab^*)\epsilon_{\mu\nu\rho\sigma} p_B^\mu s_B^\nu p_{\Lambda_c}^\rho s_{\Lambda_c}^\sigma. \end{aligned} \quad (10)$$

Here the last term gives the TP which can be seen explicitly in the rest frame of Λ_c^+ , where it takes the form $\vec{p}_B \cdot (\vec{s}_B \times \vec{s}_{\Lambda_c})$. It is important to note that the TP involves $s_{\Lambda_c^+}$, the spin of Λ_c^+ , which can be measured by observing its decay. One can, for instance, look at the scattering process $e^+e^- \rightarrow X(4630) \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ [28]. The polarization of each Λ_c can be measured in a way similar to the one employed in the decay $J/\Psi \rightarrow \Lambda \bar{\Lambda}$ [29] by

analyzing the decay of the final state particles. The produced $\Lambda_c^+ \bar{\Lambda}_c^-$ pair will sequentially decay into a pair of conjugated channels $\Lambda_c^+ \rightarrow BP(V)$ and $\bar{\Lambda}_c^- \rightarrow \bar{B}\bar{P}(\bar{V})$. The angular distribution of the decay products will contain information on the $\Lambda_c^+ \bar{\Lambda}_c^-$ polarizations and hence the TP asymmetries.

An adequate formalism to calculate angular distributions is the framework of helicity amplitudes, described for instance in Refs. [30–34]. The decay chain is described by the product of amplitudes corresponding to each reaction. For a decay $X \rightarrow YZ$, we define polar angles (θ_X, ϕ_X) describing the momentum of particle Y in the rest frame of X in a basis where the z -axis is defined by the momentum of X in the rest frame of its mother particle. The decay amplitude depends on (θ_X, ϕ_X) and is denoted by $A_{\lambda_Y \lambda_Z}^{X \rightarrow YZ}$ where λ_Y, λ_Z are the helicities of the daughter hadrons. In the process $\Lambda_c^+ \rightarrow BP$, there are two helicity amplitudes $A_{\frac{1}{2},0}$ and $A_{-\frac{1}{2},0}$. On the other hand, in Eqs. (7) and (10), a and b are the two relevant coupling parameters for the decay. It can be easily shown, using Eq (8), that the parameters $A_{\frac{1}{2},0}, A_{-\frac{1}{2},0}$ are linear combinations of S and P defined in Eq. (9). Consequently, one can get

$$Im(ab^*) \sim Im(A_{\frac{1}{2},0} A_{-\frac{1}{2},0}^*). \quad (11)$$

Defining

$$A_T = \frac{Im(A_{\frac{1}{2},0} A_{-\frac{1}{2},0}^*)}{|A_{\frac{1}{2},0}|^2 + |A_{-\frac{1}{2},0}|^2}, \quad (12)$$

and

$$\bar{A}_T = \frac{Im(\bar{A}_{\frac{1}{2},0} \bar{A}_{-\frac{1}{2},0}^*)}{|\bar{A}_{\frac{1}{2},0}|^2 + |\bar{A}_{-\frac{1}{2},0}|^2}. \quad (13)$$

the genuine T violating signal, as discussed in Eq. (6), reads [10, 19]

$$\mathcal{A}_T = \frac{1}{2} \left(\frac{Im(A_{\frac{1}{2},0} A_{-\frac{1}{2},0}^*)}{|A_{\frac{1}{2},0}|^2 + |A_{-\frac{1}{2},0}|^2} + \frac{Im(\bar{A}_{\frac{1}{2},0} \bar{A}_{-\frac{1}{2},0}^*)}{|\bar{A}_{\frac{1}{2},0}|^2 + |\bar{A}_{-\frac{1}{2},0}|^2} \right) \quad (14)$$

For the process $\Lambda_c^+ \rightarrow \Lambda \pi^+ \rightarrow (p \pi^-) \pi^+$, we can construct the CP violating observable

$$\mathcal{A}_T = \frac{1}{2} \left[\frac{Im(A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+} A_{-\frac{1}{2},0}^{*\Lambda_c \rightarrow \Lambda \pi^+})}{|A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+}|^2 + |A_{-\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+}|^2} + \frac{Im(\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-} \bar{A}_{-\frac{1}{2},0}^{*\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-})}{|\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-}|^2 + |\bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-}|^2} \right], \quad (15)$$

where the quantities involved can be extracted through the angular distribution. Without loss of generality, for spin-up Λ_c^+ the angular distribution reads

$$|M|_{(\Lambda \pi)}^2 \propto \left[\cos^2 \frac{\theta_{\Lambda_c}}{2} \cos^2 \frac{\theta_{\Lambda}}{2} \left| A_{\frac{1}{2},0}^{\Lambda \rightarrow p \pi^-} \right|^2 \right.$$

$$\begin{aligned} &+ \cos^2 \frac{\theta_{\Lambda_c}}{2} \sin^2 \frac{\theta_{\Lambda}}{2} \left| A_{-\frac{1}{2},0}^{\Lambda \rightarrow p \pi^-} \right|^2 \cdot \left| A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+} \right|^2 \\ &+ \left[\sin^2 \frac{\theta_{\Lambda_c}}{2} \sin^2 \frac{\theta_{\Lambda}}{2} \left| A_{\frac{1}{2},0}^{\Lambda \rightarrow p \pi^-} \right|^2 \right. \\ &+ \sin^2 \frac{\theta_{\Lambda_c}}{2} \cos^2 \frac{\theta_{\Lambda}}{2} \left| A_{-\frac{1}{2},0}^{\Lambda \rightarrow p \pi^-} \right|^2 \cdot \left| A_{-\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+} \right|^2 \\ &- \frac{1}{2} \sin \theta_{\Lambda_c} \sin \theta_{\Lambda} \left[\left| A_{\frac{1}{2},0}^{\Lambda \rightarrow p \pi^-} \right|^2 - \left| A_{-\frac{1}{2},0}^{\Lambda \rightarrow p \pi^-} \right|^2 \right] \\ &\cdot \left[\cos \phi_{\Lambda} Re(A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+} A_{-\frac{1}{2},0}^{*\Lambda_c \rightarrow \Lambda \pi^+}) - \right. \\ &\quad \left. \sin \phi_{\Lambda} Im(A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda \pi^+} A_{-\frac{1}{2},0}^{*\Lambda_c \rightarrow \Lambda \pi^+}) \right], \quad (16) \end{aligned}$$

and for a spin-down $\bar{\Lambda}_c^-$ it reads

$$\begin{aligned} |\bar{M}|_{(\Lambda \pi)}^2 \propto & \left[\sin^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \cos^2 \frac{\theta_{\bar{\Lambda}}}{2} \left| \bar{A}_{\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p} \pi^+} \right|^2 \right. \\ &+ \sin^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \sin^2 \frac{\theta_{\bar{\Lambda}}}{2} \left| \bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p} \pi^+} \right|^2 \cdot \left| \bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-} \right|^2 \\ &+ \left[\cos^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \sin^2 \frac{\theta_{\bar{\Lambda}}}{2} \left| \bar{A}_{\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p} \pi^+} \right|^2 \right. \\ &+ \cos^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \cos^2 \frac{\theta_{\bar{\Lambda}}}{2} \left| \bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p} \pi^+} \right|^2 \cdot \left| \bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-} \right|^2 \\ &+ \frac{1}{2} \sin \theta_{\bar{\Lambda}_c} \sin \theta_{\bar{\Lambda}} \left[\left| \bar{A}_{\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p} \pi^+} \right|^2 - \left| \bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p} \pi^+} \right|^2 \right] \\ &\cdot \left[\cos \phi_{\bar{\Lambda}} Re(\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-} \bar{A}_{-\frac{1}{2},0}^{*\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-}) - \right. \\ &\quad \left. \sin \phi_{\bar{\Lambda}} Im(\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-} \bar{A}_{-\frac{1}{2},0}^{*\bar{\Lambda}_c \rightarrow \bar{\Lambda} \pi^-}) \right]. \quad (17) \end{aligned}$$

The first term in Eq. (15) can be obtained from fitting to the angular dependence in Eq. (16) and the second term can be obtained from fitting to Eq. (17). We also note that if the polarization of the proton is known, each angular distribution in Eq. (16) and Eq. (17) can be isolated into two terms corresponding to the polarization states of the proton.

We next turn to the analysis of $\Lambda_c^+ \rightarrow BV$ decays. The general decay amplitude for this process can be written as [26, 27]

$$\begin{aligned} \mathcal{M}_V &= A(\Lambda_c^+ \rightarrow BV) \\ &= \epsilon_{V\mu}^* \bar{u}_B [(p_{\Lambda_c}^\mu + p_B^\mu)(a + b\gamma_5) \\ &\quad + \gamma^\mu (x + y\gamma_5)] u_{\Lambda_c} \quad (18) \end{aligned}$$

where $\epsilon_{V\mu}$ is the polarization of the vector meson V , a, b, x and y are coupling parameters. In the rest frame of Λ_c^+ , $p_V = (E_V, 0, 0, |\vec{p}_V|)$ and $p_B = (E_B, 0, 0, -|\vec{p}_V|)$, thus the term $\epsilon_{V\mu}^* (p_{\Lambda_c}^\mu + p_B^\mu)$ can be non-zero only for the longitudinal polarized V . Evaluating $|\mathcal{M}_V|^2$ we get the relevant TP terms (refer to Ref. [27]) as

$$\begin{aligned} |\mathcal{M}_V|_{t.p.}^2 &= 2Im(ab^*) |\epsilon_V \cdot (p_{\Lambda_c} + p_B)|^2 \cdot \epsilon_{\mu\nu\rho\sigma} p_B^\mu s_B^\nu p_{\Lambda_c}^\rho s_{\Lambda_c}^\sigma \\ &\quad + 2Im(xy^*) \epsilon_{\mu\nu\rho\sigma} [\epsilon_V \cdot s_B p_B^\mu p_{\Lambda_c}^\nu s_{\Lambda_c}^\rho \epsilon_V^\sigma] \end{aligned}$$

$$\begin{aligned}
& -\epsilon_V \cdot p_B s_B^\mu p_{\Lambda_c}^\nu s_{\Lambda_c}^\rho \epsilon_V^\sigma \\
& +\epsilon_V \cdot s_{\Lambda_c} p_B^\mu s_B^\nu \epsilon_V^\rho p_{\Lambda_c}^\sigma \\
& -\epsilon_V \cdot p_{\Lambda_c} p_B^\mu s_B^\nu \epsilon_V^\rho s_{\Lambda_c}^\sigma] \\
& +2\epsilon_V \cdot (p_{\Lambda_c} + p_B) \epsilon_{\mu\nu\rho\sigma} \\
& \cdot [Im(ax^* + by^*) p_B^\mu s_B^\nu p_{\Lambda_c}^\rho \epsilon_V^\sigma \\
& +m_{\Lambda_c} Im(bx^* + ay^*) p_B^\mu s_B^\nu s_{\Lambda_c}^\rho \epsilon_V^\sigma \\
& -Im(ax^* - by^*) p_B^\mu p_{\Lambda_c}^\nu s_{\Lambda_c}^\rho \epsilon_V^\sigma \\
& -m_B Im(ay^* - bx^*) s_B^\mu p_{\Lambda_c}^\nu s_{\Lambda_c}^\rho \epsilon_V^\sigma] (19)
\end{aligned}$$

In Eq. (19), aside from the first term, all the other TP terms involve the polarization of the vector meson, and these TP terms will vanish after summing over the polarizations of the vector meson. In Eq. (19), the first TP term survives only for a longitudinal polarized V , and has the same structure as in the $\Lambda_c^+ \rightarrow BP$ decay. For the process $\Lambda_c^+ \rightarrow \Lambda\rho^+ \rightarrow (p\pi^+)(\pi^+\pi^0)$, we can define the TP asymmetry as

$$\begin{aligned}
\mathcal{A}_T = \frac{1}{2} & \left(\frac{Im(A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+} A_{-\frac{1}{2},0}^{*\Lambda_c \rightarrow \Lambda\rho^+})}{|A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+}|^2 + |A_{-\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+}|^2} \right. \\
& \left. + \frac{Im(\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-} \bar{A}_{-\frac{1}{2},0}^{*\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-})}{|\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-}|^2 + |\bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-}|^2} \right) \quad (20)
\end{aligned}$$

The relevant terms(r.l.) occurring in the angular distribution are listed below. For spin-up Λ_c^+ one has,

$$\begin{aligned}
|M|_{r.l.}^2 \propto & \left[\cos^2 \frac{\theta_{\Lambda_c}}{2} \cos^2 \frac{\theta_{\Lambda}}{2} \cos^2 \theta_\rho |A_{\frac{1}{2},0}^{\Lambda \rightarrow p\pi^-}|^2 \right. \\
& + \cos^2 \frac{\theta_{\Lambda_c}}{2} \sin^2 \frac{\theta_{\Lambda}}{2} \cos^2 \theta_\rho |A_{-\frac{1}{2},0}^{\Lambda \rightarrow p\pi^-}|^2 \cdot |A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+}|^2 \\
& + \left[\sin^2 \frac{\theta_{\Lambda_c}}{2} \sin^2 \frac{\theta_{\Lambda}}{2} \cos^2 \theta_\rho |A_{\frac{1}{2},0}^{\Lambda \rightarrow p\pi^-}|^2 \right. \\
& + \sin^2 \frac{\theta_{\Lambda_c}}{2} \cos^2 \frac{\theta_{\Lambda}}{2} \cos^2 \theta_\rho |A_{-\frac{1}{2},0}^{\Lambda \rightarrow p\pi^-}|^2 \cdot |A_{-\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+}|^2 \\
& - \frac{1}{2} \sin \theta_{\Lambda_c} \sin \theta_{\Lambda} \cos^2 \theta_\rho \left[|A_{\frac{1}{2},0}^{\Lambda \rightarrow p\pi^-}|^2 - |A_{-\frac{1}{2},0}^{\Lambda \rightarrow p\pi^-}|^2 \right] \\
& \cdot \left[\cos \phi_{\Lambda} Re(A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+} A_{-\frac{1}{2},0}^{*\Lambda_c \rightarrow \Lambda\rho^+}) - \right. \\
& \left. \left. \sin \phi_{\Lambda} Im(A_{\frac{1}{2},0}^{\Lambda_c \rightarrow \Lambda\rho^+} A_{-\frac{1}{2},0}^{*\Lambda_c \rightarrow \Lambda\rho^+}) \right] \right], \quad (21)
\end{aligned}$$

and for a spin-down $\bar{\Lambda}_c^-$

$$\begin{aligned}
|\bar{M}|_{r.l.}^2 \propto & \left[\sin^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \cos^2 \frac{\theta_{\bar{\Lambda}}}{2} \cos^2 \theta_\rho |\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p}\pi^+}|^2 \right. \\
& + \sin^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \sin^2 \frac{\theta_{\bar{\Lambda}}}{2} \cos^2 \theta_\rho |\bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p}\pi^+}|^2 \cdot |\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-}|^2 \\
& + \left[\cos^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \sin^2 \frac{\theta_{\bar{\Lambda}}}{2} \cos^2 \theta_\rho |\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p}\pi^+}|^2 \right. \\
& + \cos^2 \frac{\theta_{\bar{\Lambda}_c}}{2} \cos^2 \frac{\theta_{\bar{\Lambda}}}{2} \cos^2 \theta_\rho |\bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p}\pi^+}|^2 \cdot |\bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-}|^2 \\
& + \frac{1}{2} \sin \theta_{\bar{\Lambda}_c} \sin \theta_{\bar{\Lambda}} \cos^2 \theta_\rho \left[|\bar{A}_{\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p}\pi^+}|^2 - |\bar{A}_{-\frac{1}{2},0}^{\bar{\Lambda} \rightarrow \bar{p}\pi^+}|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& \cdot \left[\cos \phi_{\bar{\Lambda}} Re(A_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-} A_{-\frac{1}{2},0}^{*\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-}) - \right. \\
& \left. \sin \phi_{\bar{\Lambda}} Im(A_{\frac{1}{2},0}^{\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-} A_{-\frac{1}{2},0}^{*\bar{\Lambda}_c \rightarrow \bar{\Lambda}\rho^-}) \right]. \quad (22)
\end{aligned}$$

In experiment, the sizes and the relative phase between $A_{\frac{1}{2},0}$'s and $A_{-\frac{1}{2},0}$'s can be extracted by performing a full angular analysis given by Eqs. (16), (17), (21) and (22). These expressions represent the main results of the paper. The measurement of angular distributions and TP asymmetries can be done in a reliable way with large data samples.

Note that, Λ_c^+ decays are different from Λ_b decays, in the sense that in Λ_b decay even the SM can give large TP asymmetries [27, 35, 36]. However CP violation in the charm sector is tiny in the SM, as indicated above, and hence any future non-zero signal of the CP violation in Λ_c^+ decays will be a signal of NP. We now estimate the size of the TP asymmetry in a model of NP. We begin with the SM where the effective Hamiltonian for weak charm decays is given by [37, 38]

$$H_{eff}^q = \frac{G_F}{\sqrt{2}} [V_{cs} V_{ud}^* (c_1 O_1^q + c_2 O_2^q)] + h.c., \quad (23)$$

where

$$\begin{aligned}
O_1^q &= \bar{s} \gamma_\mu (1 - \gamma_5) c \bar{u} \gamma^\mu (1 - \gamma_5) d, \\
O_2^q &= \bar{s}_\alpha \gamma_\mu (1 - \gamma_5) c_\beta \bar{u}_\alpha \gamma^\mu (1 - \gamma_5) d_\beta, \quad (24)
\end{aligned}$$

and $h.c.$ means Hermitian conjugate. We will use the Wilson's coefficients at the charm scale as $c_1 = 1.27$, $c_2 = -0.53$ [37, 38].

In the above we have neglected penguin contributions that are tiny for the charm quark decay. In the absence of the penguin contribution there is no TP asymmetry in the SM as there is only one weak phase in the amplitude.

We now turn to a new physics model. We will consider a two Higgs doublet model (2HDM) in which the decay $\Lambda_c^+ \rightarrow BP$ can get a contribution through a charged Higgs exchange. The 2HDM is a simple extension of the SM and is an effective low energy limit of many extensions of the SM. We will provide a rough estimate of the T.P asymmetry in this model. Our aim is to merely show that it is possible for NP to generate a significant TP asymmetry in this decay. The general Lagrangian for the $H^\pm f f'$ interaction is given by

$$\begin{aligned}
\mathcal{L}^{2HDM} = & H^+ \left[\frac{y_c}{2} \bar{c}(1 - \gamma_5) s + \frac{y_u}{2} \bar{u}(1 - \gamma_5) d + \frac{y_s}{2} \bar{c}(1 + \gamma_5) s \right] \\
& + H^+ \left[\frac{y_d}{2} \bar{u}(1 + \gamma_5) \right] d + h.c. \quad (25)
\end{aligned}$$

where $y_{c,s,u,d}$ are complex Yukawa couplings. There can also be charged Higgs couplings for the b quark which can cause deviations from the SM in B decays. However, in general the b quark coupling or the third generation couplings are not related to the couplings of the first two generations. Hence constraints on new physics from b quark decays do not apply to charm quark decays in

general. If the Higgs couples dominantly to the down quarks of the first two generation then we can assume $y_{c,u} \ll y_{s,d}$. Integrating out the heavy charged higgs leads to the effective Hamiltonian for $\Lambda_c^+ \rightarrow BP$ transition

$$H_{eff}^{NP} = \frac{G_F}{\sqrt{2}} \frac{y_s y_d}{g^2} \frac{2M_W^2}{m_{H^\pm}^2} \bar{s}(1 - \gamma_5) c \bar{u}(1 + \gamma_5) d, \quad (26)$$

where g is the weak SM coupling. We will now focus on the specific decay $\Lambda_c^+ \rightarrow \Lambda \pi^+$. In the presence of new physics we can write the amplitude for $\Lambda_c^+ \rightarrow \Lambda \pi^+$ as

$$A(\Lambda_c^+ \rightarrow \Lambda \pi) = \bar{u}_\Lambda [a_{SM}(1 + r_a) + b_{SM}(1 + r_b)\gamma_5] u_{\Lambda_c} \quad (27)$$

where a_{SM} and b_{SM} are the SM contributions and $r_{a,b}$ are the ratios of the NP contributions relative to the SM contributions. To estimate $r_{a,b}$ we will use factorization and use the heavy quark limit for the charm quark.

To proceed with our calculations we use the following results for the matrix elements,

$$\begin{aligned} \langle \Lambda | \bar{s}(1 - \gamma_5) c | \Lambda_c^+ \rangle &= \frac{q_\mu}{m_c} \langle \Lambda | \bar{s} \gamma^\mu (1 + \gamma_5) c | \Lambda_c^+ \rangle \\ \langle \pi^+ | \bar{u} \gamma^\mu (1 - \gamma_5) d | 0 \rangle &= i f_\pi q^\mu \\ \langle \pi^+ | \bar{u} (1 + \gamma_5) d | 0 \rangle &= -i f_\pi \frac{m_\pi^2}{m_u + m_d}, \end{aligned} \quad (28)$$

where $q = p_{\Lambda_c} - p_\Lambda$, f_π and m_π are the pion decay constant and its mass, $m_{u,d}$ are the up and down quark masses. One can now compute $r_{a,b}$ in Eq. (27) as,

$$\begin{aligned} r_b &= -r_a = r \\ r &= e^{i\phi} \frac{|y_s y_d|}{a_1 V_{cs} V_{ud} g^2} \frac{2M_W^2}{m_{H^\pm}^2} \frac{m_\pi^2}{(m_u + m_d) m_c}, \end{aligned} \quad (29)$$

where we have written $y_s y_d = |y_s y_d| e^{i\phi}$ with ϕ being the new physics CP violating phase and $a_1 = c_1 + c_2/N_c$. The Yukawa couplings $y_{s,d}$ are unknown and can be $O(1)$. Assuming the theory to be weakly coupled, we will take $y_{s,d} \sim g$ where g is the weak coupling. Using $|y_s y_d| \sim g^2$, $a_1 = 0.94$, $V_{cs} = 0.973$ [13] and $V_{ud} = 0.974$ [13] we find $\frac{|y_s y_d|}{a_1 V_{cs} V_{ud} g^2} \sim 1.14$ which gives $|r| \approx 0.14$ for $m_{H^\pm} = 300$ GeV. In our calculation we have taken $m_c = 1.4$ GeV,

$m_d = 10$ MeV and $m_u = 5$ MeV [13]. The operators in the two Higgs doublet model can in principle be constrained from $D(D_s)$ decays. For instance, the new physics operators can change the rate of $D(D_s)$ decays. However, as we have shown above the size of NP is not that large and is at the 10-15% level. Such size of NP are consistent with the measured D decay rates because of hadronic uncertainties in the theoretical calculations. For the same reason this size of NP is also consistent with direct CP measurements. As we have indicated in the paper TP have advantages over other CP measurements such as direct CP asymmetry, if strong phases are small, and in general TP asymmetries complement other CP violation measurements. As indicated above the scalar-pseudoscalar operators of the model will not contribute to $D(D_s) \rightarrow VV$ at tree level but will contribute to TP asymmetries in $\Lambda_c \rightarrow BP$ decays and hence can be constrained by measurements in these decays. Now we can estimate the TP asymmetry $\sim 2|r| \sin \phi \frac{2a_{SM} b_{SM}^*}{|a_{SM}|^2 + |b_{SM}|^2}$. To a good approximation in the SM, $a_{SM} = \frac{m_{\Lambda_c} - m_\Lambda}{m_{\Lambda_c} + m_\Lambda} b_{SM}$. One therefore obtains the TP asymmetry $\sim 0.18 \sin \phi$ and so a large TP is possible if $\sin \phi \sim 1$. Hence, it is possible that future high luminosity experiments could provide evidence for CP violation in Λ_c^+ decays by exploiting the method of CP violating TP asymmetry. One can search for TP asymmetries at BEPC-II/BES-III or future Super τ -charm factory with luminosity about 100 times as large as BEPC-II [39, 40].

We now consider the potential sensitivities of the CP violating observables \mathcal{A}_T at BES-III and the Super τ -charm factory. From Eqs. (4) and (5), for a small asymmetry, there is a general result that the error in measurements is approximately estimated as $1/\sqrt{N_{obs}}$, where N_{obs} is the total number of events observed [9, 10, 41, 42]. For the process $e^+ e^- \rightarrow X(4630) \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$, taking the cross section of $0.5 nb^{-1}$ into account [28], $2.5 \times 10^6 \Lambda_c^+ \bar{\Lambda}_c^-$ pairs will be collected with an integrated luminosity of $5 fb^{-1}$ at $X(4630)$ peak for one year at BES-III. Table I lists some promising $\Lambda_c^+ \rightarrow BP$ channels to search for TP asymmetries. The expected statistical errors are estimated by using $2.5 \times 10^6 \Lambda_c^+ \bar{\Lambda}_c^-$ pairs at BES-III and $2.5 \times 10^8 \Lambda_c^+ \bar{\Lambda}_c^-$ pairs at a Super τ -charm factory. Table II shows the results relevant to $\Lambda_c^+ \rightarrow BV$ decays. The projected efficiencies are estimated from the current status of BES-III and the branching ratios are obtained from Ref. [13].

For the listed BP and BV modes in Table I and Table II, the expected error in TP asymmetry measurement at BES-III are estimated to be of the order of $\mathcal{O}(10^{-2})$.

At Super τ -charm factory with $2.5 \times 10^8 \Lambda_c^+ \bar{\Lambda}_c^-$ pairs, it will be reduced by one order of magnitude. Hence the prospect of measuring TP asymmetries in processes

BP	Br	Eff.(ϵ)	Expected errors at BES-III ($\times 10^{-2}$)
$\Lambda\pi^+ \rightarrow (p\pi^-)\pi^+$	6.8×10^{-3}	0.82	0.85
$\Lambda K^+ \rightarrow (p\pi^-)K^+$	3.2×10^{-4}	0.75	4.08
$\Lambda(1520)\pi^+ \rightarrow (pK^-)\pi^+$	8.1×10^{-3}	0.75	0.81
$\Sigma^0\pi^+ \rightarrow (\Lambda\gamma)\pi^+$	1.0×10^{-2}	0.62	0.80
$\Sigma^0 K^+ \rightarrow (\Lambda\gamma)K^+$	4.0×10^{-4}	0.56	4.23
$\Sigma^+\pi^0 \rightarrow (p\pi^0)\pi^0$	5.0×10^{-3}	0.60	1.15
$\Sigma^+\eta \rightarrow (p\pi^0)(\pi^+\pi^-\pi^0)$	8.2×10^{-4}	0.52	3.06
$\Xi^0 K^+ \rightarrow (\Lambda\pi^0)K^+$	2.6×10^{-4}	0.57	5.20

TABLE I. The promising (BP) modes with branching fractions, efficiencies and expected errors on the TP asymmetries: the corresponding expected errors are estimated by assuming $2.5 \times 10^6 \Lambda_c^+ \bar{\Lambda}_c^-$ pairs collected at BES-III with one year luminosity.

BV	Br	Eff.(ϵ)	Expected errors at BES-III ($\times 10^{-2}$)
$\Lambda\rho^+ \rightarrow (p\pi^-)(\pi^+\pi^0)$	$3.2 \times 10^{-2*}$	0.65	0.44
$\Sigma(1385)^+\rho^0 \rightarrow (\Lambda\pi^+)(\pi^+\pi^-)$	2.4×10^{-3}	0.69	1.55
$\Sigma^+\rho^0 \rightarrow (p\pi^0)(\pi^+\pi^-)$	$0.7 \times 10^{-2*}$	0.62	0.96
$\Sigma^+\omega \rightarrow (p\pi^0)(\pi^+\pi^-\pi^0)$	1.4×10^{-2}	0.49	0.76
$\Sigma^+\phi \rightarrow (p\pi^0)(K^+K^-)$	0.8×10^{-3}	0.52	3.10
$\Sigma^+ K^{*0} \rightarrow (p\pi^0)(K^-\pi^+)$	0.7×10^{-3}	0.57	3.17

TABLE II. The promising (BV) modes with branching fractions, efficiencies and expected errors on the TP asymmetries: the corresponding expected errors are estimated by assuming that $2.5 \times 10^6 \Lambda_c^+ \bar{\Lambda}_c^-$ pairs collected at BES-III with one year luminosity.

$\Lambda_c^+ \rightarrow BP$ and $\Lambda_c^+ \rightarrow BV$ at BES-III and the Super τ -charm factory are very promising. In Table II, the branching ratios with asterisk have not been measured, and we have set the branching fractions of the process $\Lambda_c^+ \rightarrow \Lambda\rho^+$ and $\Lambda_c^+ \rightarrow \Sigma^+\rho^0$ to be at the upper limit values in PDG [13]. Note that in table I and II, the estimated efficiencies are just rough estimations according to the design of BEPC-II/BES-III. In the future, careful measurements at BES-III of both the efficiencies and branching fractions are suggested. A more realistic analysis would require a likelihood fit to the full angular dependence of the $\Lambda_c^+ \rightarrow BP \rightarrow (B'P')P$ mode (B' , P' denote the daughter baryon and pseudoscalar decay products of the parent particle B .) and of the $\Lambda_c^+ \rightarrow BV \rightarrow (B''P'')(PP)$ mode (B'' , P'' denote the daughter baryon and pseudoscalar decay products of the parent particle B and (PP) are the pseudoscalars from the decay of the vector meson V .) Systematics will arise from mis-reconstructions as some $B'P'$ can actually come from other baryon resonances or non-resonant background contributions. In view of the experimental realities, we expect that these systematics will dominate the final result. Their precise estimates in the experiment is beyond the scope of this paper.

In conclusion, we studied the CP violation in $\Lambda_c^+ \rightarrow BP$ and $\Lambda_c^+ \rightarrow BV$ decay modes in which the T -odd CP violating TP correlations were examined. Here, B , P and

V denotes a light spin- $\frac{1}{2}$ baryon, pseudoscalar and a vector mesons, respectively. We showed how the genuine CP violating observable can be constructed and extracted from angular distributions. These CP violating observable depends on the cosine of the strong phases, and if the strong phases are small, they are potentially more sensitive to new CP violating phases beyond the SM than the direct CP violating signals that depend on the sine of the strong phases. We provided estimates of the TP asymmetries in a model of NP and found that NP can produce large TP asymmetries. Finally, we considered the potential sensitivities on the CP violating observable \mathcal{A}_T at BES-III and at the Super τ -charm factory. Our numerical estimates showed that the error in the measurements were very small and could reach the magnitude of $\mathcal{O}(10^{-3})$. Hence, we concluded that the prospect of measuring TP asymmetries in processes $\Lambda_c^+ \rightarrow BP$ and $\Lambda_c^+ \rightarrow BV$ at BES-III and at the Super τ -charm factory were very promising.

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